Radiography: Fundamental Principles

Charles E. Willis, Ph.D. DABR FAAPM
Associate Professor
Department of Imaging Physics
The University of Texas M. D. Anderson Cancer Center
Houston, Texas

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Overview:

- Will review fundamentals of ordinary radiographic examinations, *aka* plain, or plane projection radiography
- Will consider how these characteristics affect dose and image quality
- Will *not* discuss specialized forms of projection radiography, such as mammography, tomography, angiography, dual energy subtraction imaging

Ordinary radiographic examinations are cleverly designed ...

- To position the patient …
- … in an x-ray beam …
  - *... of sufficient quality and quantity ...*
- … to project the anatomy of interest …
- … onto a flat detector of radiation.

- Additional projections (views) are obtained in order to visualize clinical features in three dimensions and to avoid overlying anatomic structures.

Radiographic examinations are named according to certain conventions

- Anatomy of interest
  - *Chest, abdomen, pelvis, skull, hand, etc.*
- Each view is named according to the position of the anatomy with respect to the entry of the central ray (CR!) of the x-ray beam
  - *Antero-posterior (AP) Chest, Lateral (LAT) Hip, Oblique Elbow*
- Each view is further described by the laterality of the body part
  - *AP Right Hand*
- Each view may be further specified to indicate the side of the body that is closest to the image receptor
  - *Left Anterior Oblique (LAO) Ribs*
- Certain positions have been named for the person who first reported them
  - *Caldwell, Towne, Waters, Lindblom, Ferguson, Judd*

The position of the patient in the x-ray beam affects the patient's radiation dose

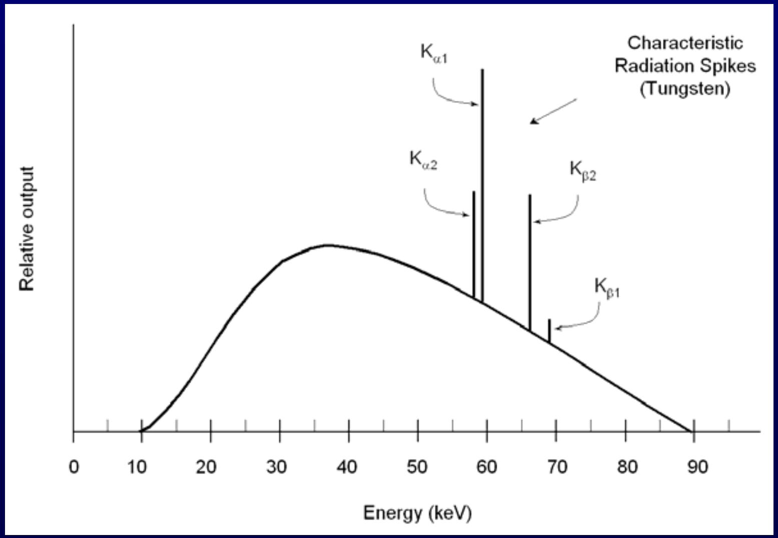
- The patient's body attenuates the beam as it passes though the body
  - *More energy is deposited in organs located near the entry of the beam than near the exit of the beam*
    - Exposure-to-dose conversion factor for breasts is 14X higher for AP *vs.* PA Chest view (Tables 23-24, HHS Pub 89-8031)
- The field of view (FOV) affects patient dose in two ways
  - *Organs within the FOV are irradiated unless shielded*
  - *The larger the FOV, the more scatter is produced increasing the depth dose for the same entrance exposure*
    - About 10% higher for 35x35cm vs. 15x15cm (Table B.8 NCRP 102)

The position of the patient in the x-ray beam also affects image quality

- The anatomy of interest must be properly oriented with respect to the CR of the x-ray beam, otherwise clinical features will be incorrectly projected
  - *Rotation=>distortion*
- The FOV affects image quality
  - *must be wide enough to include the organs of interest*
  - *should be limited to reduce scatter*
  - *Scatter degrades subject contrast*
  - *Features included in the FOV affect digital image processing*
    - Dense objects (mandible, hardware, shields)=>loss of contrast
    - Too much uncovered area (under-collimation, boundary not detected)=>loss of contrast
  - *Location of the FOV on the image receptor can also affect digital image processing*
    - Centering, multiple FOV's, boundaries of FOV

X-rays are produced when electrons slam into a target!

- Two kinds of x-rays generated
  - *Braking radiation (Bremsstrahlung)*
  - *Characteristic Radiation (from the target)*
- A spectrum of energies is produced

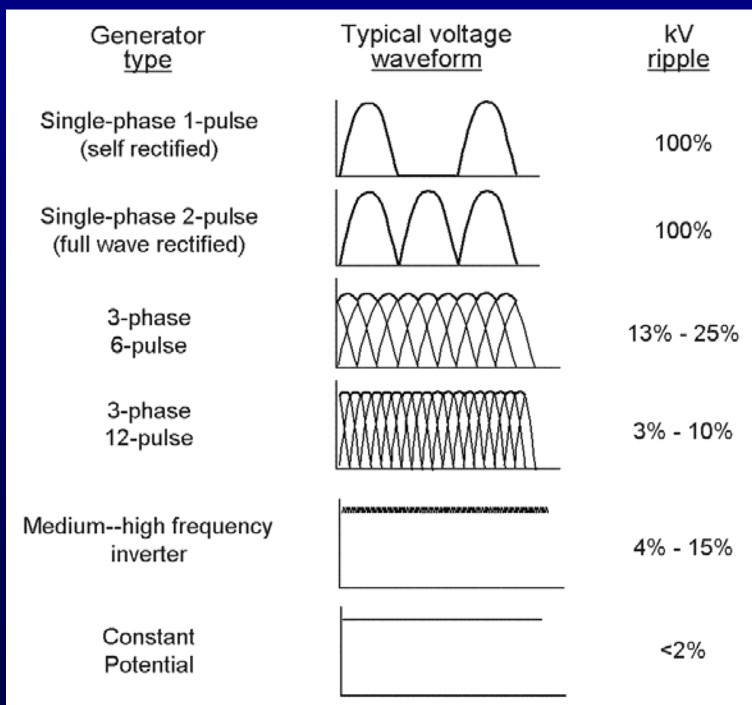


90 kVp

Fig 5-5, Bushberg et al. 2nd Ed

The quality of the x-ray spectrum is affected by rectification of the supply voltage

- The closer to constant potential, the higher the average energy of the x-ray spectrum



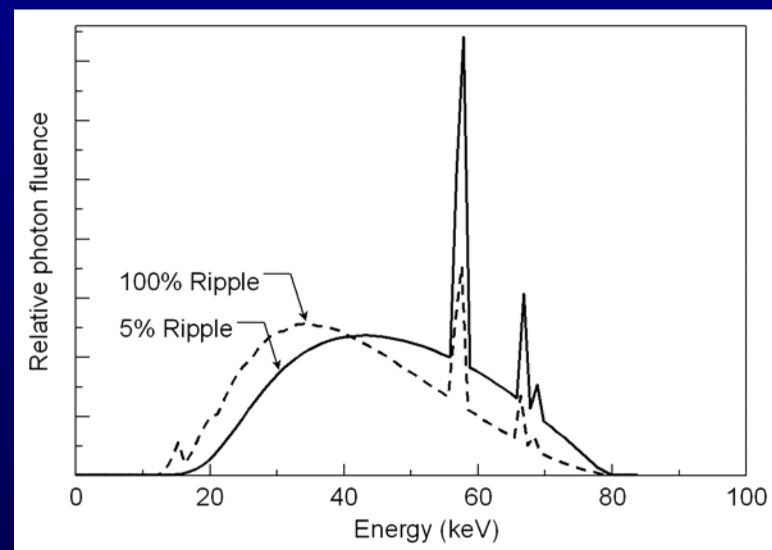


Fig 5-33 and 5-37, Bushberg et al. 2nd Ed

The quality of the x-ray spectrum is also affected by filtration

- Filtration
  - *Inherent filtration (tube and collimator assembly)*
  - *Added filtration (pre-patient filtration)*

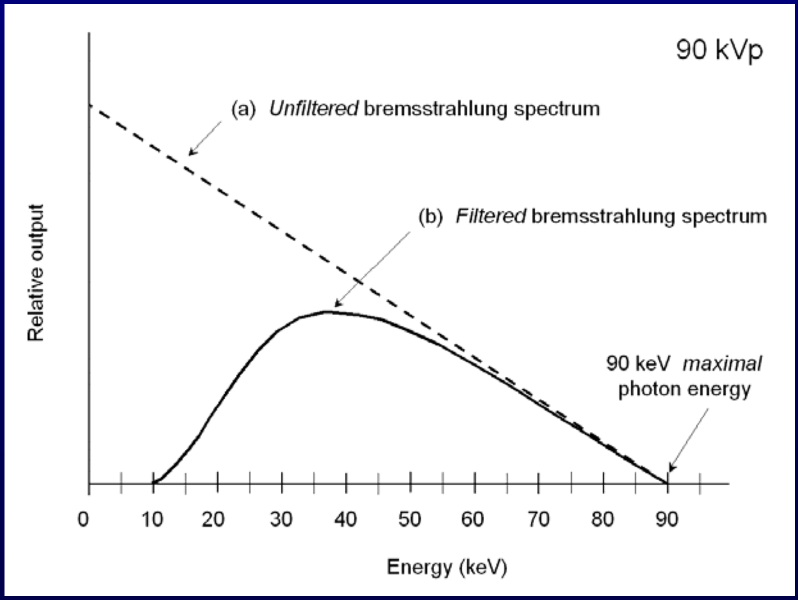
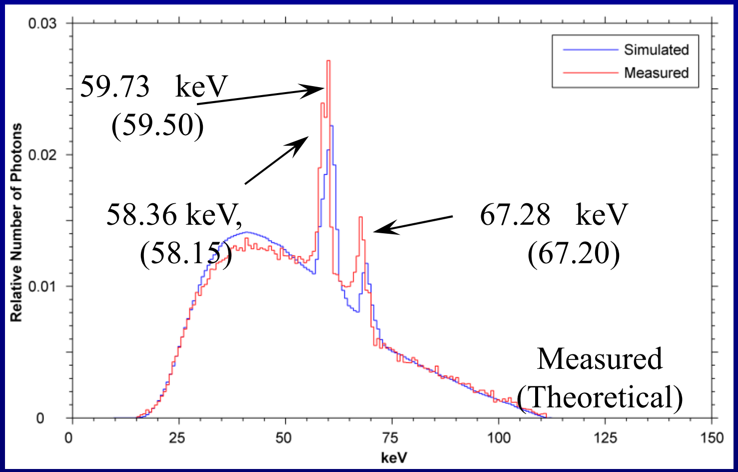
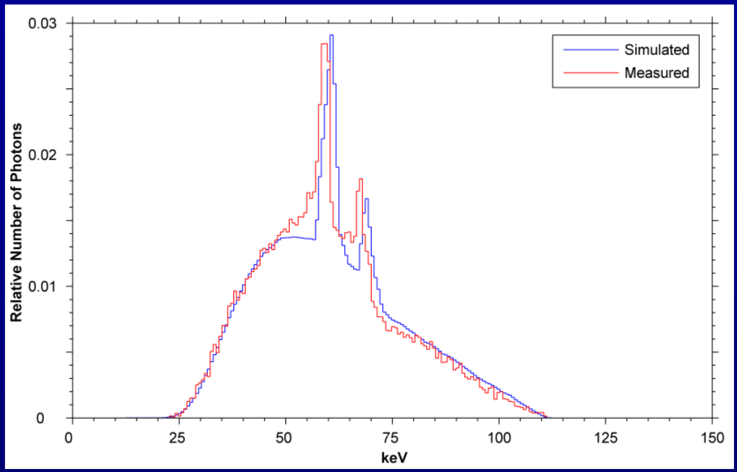


Fig 5-2, Bushberg et al. 2nd Ed.

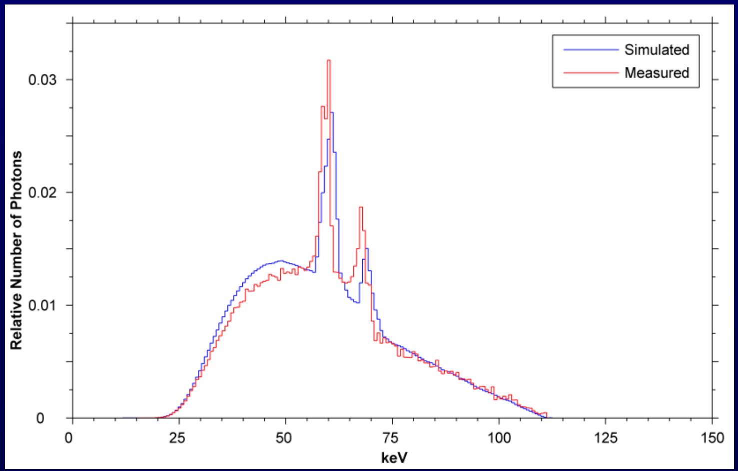
Additional filtration modifies the x-ray spectrum



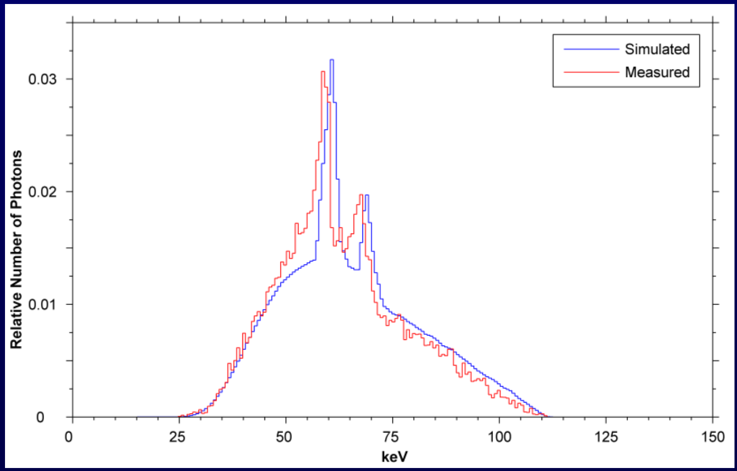
No Cu



0.2mm Cu



No Cu + 1HVL Al

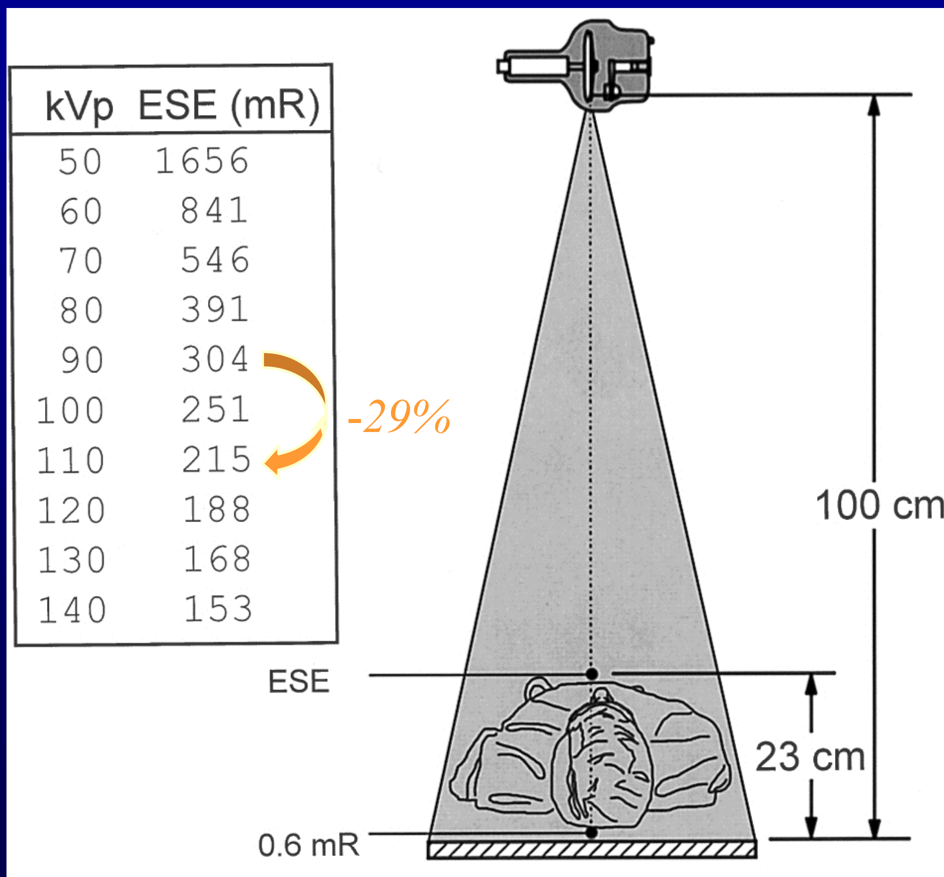


0.2 mm Cu +1HVL Al

The quality of the x-ray beam is characterized by its penetrating ability

- The half-value layer (HVL) is the thickness of material (typically Aluminum) necessary to reduce the x-ray exposure in half under narrow beam conditions ("good geometry").
- The minimum half-value layer (HVL) as a function of kVp is regulated for radiographic systems.
- For a polychromatic x-ray beam the additional amount of material needed to reduce the exposure from ½ to ¼ is greater than the 1st HVL.
  - *The ratio of HVL_1 to HVL_2 is called the "homogeneity coefficient"*
- The entire energy spectrum can simulated by knowing two of the following:
  - *kVp, HVL_1, HVL_2*

The quality of the x-ray beam affects patient exposure in ordinary radiography …and dose!



-29%

HVL	*E* (μSv)
2.0	850
2.3	490
2.6	352
3.0	288
3.3	239
3.6	215
4.0	196
4.3	178
4.6	165
5.0	159

-18%

Fig 6-20, Bushberg et al. 2nd Ed

The quantity of x-rays produced depends on technical factors (a.k.a. "technique")

- Accelerating potential (kiloVolts peak, kVp)
  - *Exposure* α *kVp*^{2}
- Beam/tube current (milliAmpere-seconds, mAs)

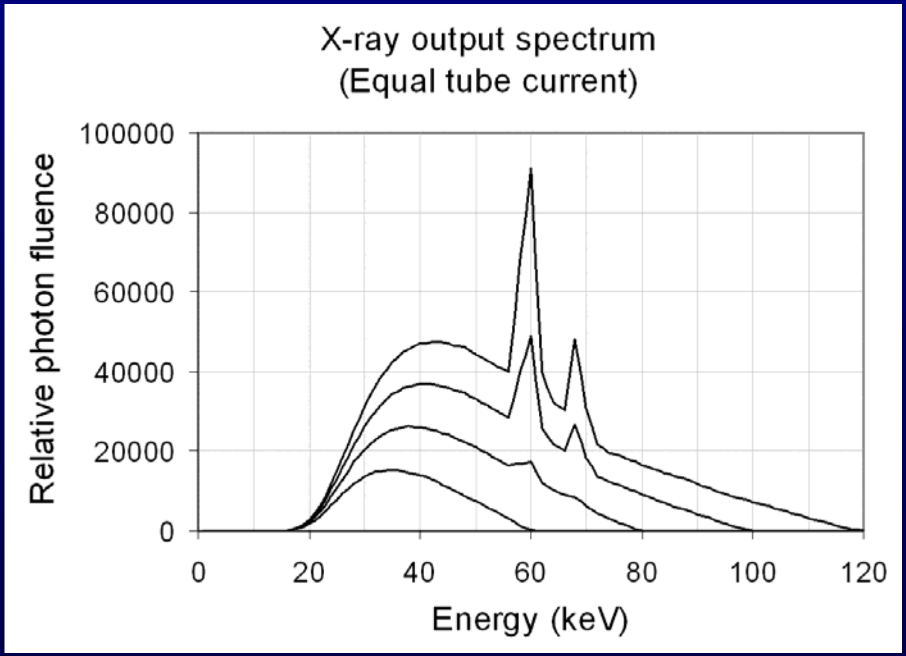


Fig 5-36, Bushberg et al. 2nd Ed

High mA stations are used to deliver the exposure in the shortest possible time

- Short exposure times avoid motion during imaging
  - *Breath-holding is requested*
  - *Cardiac motion still occurs*
- For some exams, longer exposure times are preferred
  - *Deliberate "breathing technique"- LAT T-spine*
  - *In the case of Automatic Exposure Control (AEC), high mA stations may result in exposures shorter than AEC response time (<5 ms)*

X-rays are emitted in all directions

- Some are blocked by the tube housing
- Some are blocked by the collimator blades
- Some are allowed to travel toward the patient and detector
- A light indicates where the radiation field is projected

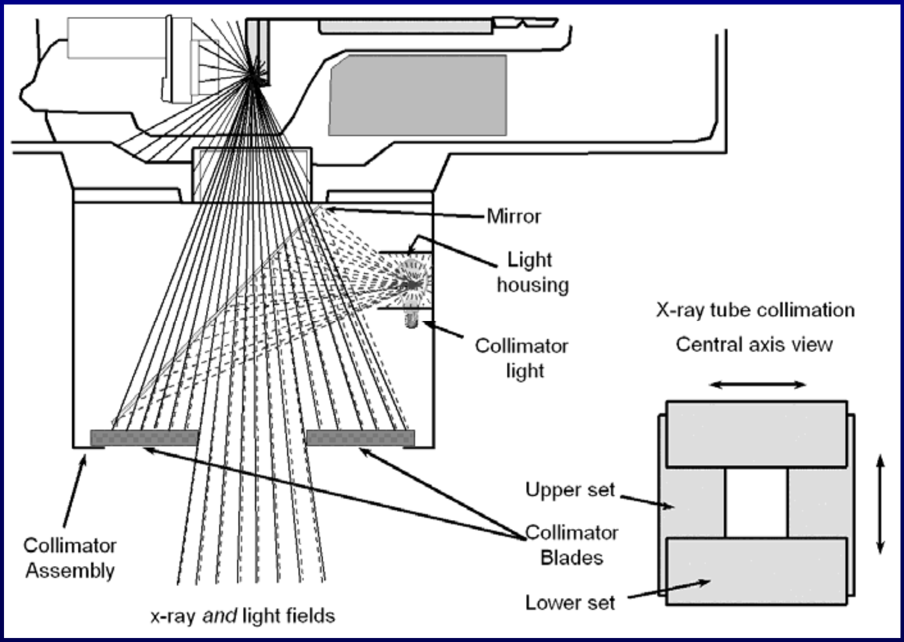


Fig 5-18, Bushberg et al. 2nd Ed

At diagnostic energies, x-rays interact with matter mainly by two processes

- Photo-electric effect
- Compton scattering
- Both about equally probable at 20 keV in soft tissue
  - *40 keV in bone*

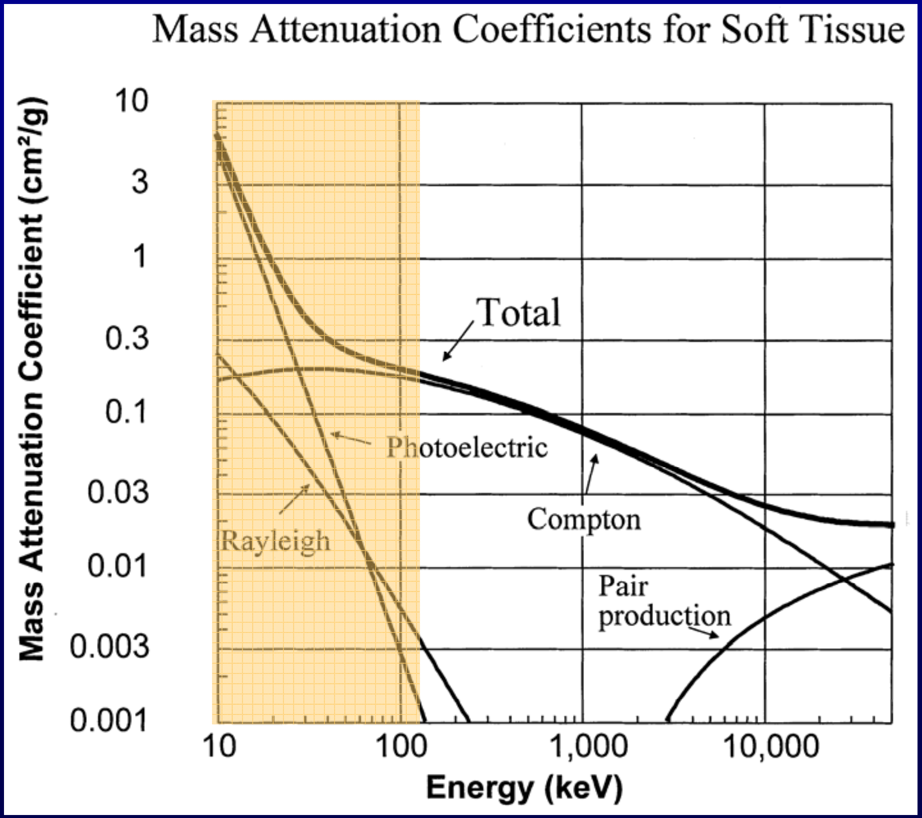


Fig 3-13, Bushberg et al. 2nd Ed

X-rays are attenuated differently according to …

- Their energy
- The composition of material
  - *Density (ρ)*
  - *Atomic number (Z)*
  - $N=N_o e^{-(\mu/\rho)\rho x}$
- The thickness of material
  - $N=N_o e^{-\mu x}$
  - $HVL= 0.693/\mu$

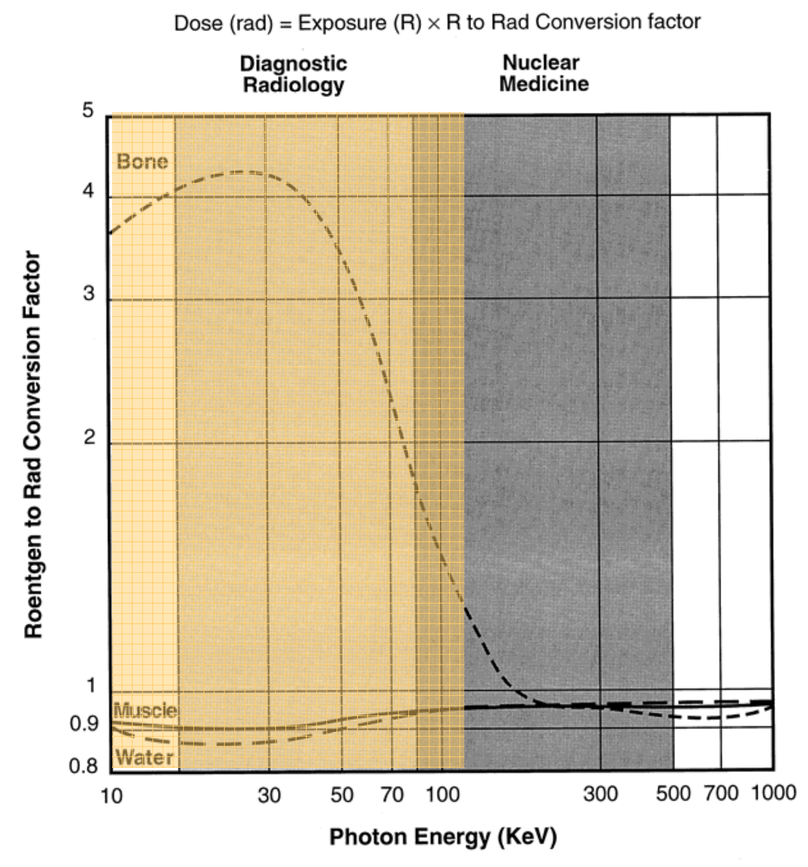


Fig 3-17, Bushberg et al. 2nd Ed

X-ray imaging is a quest for contrast!

- We can visualize anatomic features because they attenuate x-rays to different extents

$$C_s = (A\text{-}B)/A$$

$$A = N_o e^{-\mu x}$$
$$B = N_o e^{-\mu (x+z)}$$

$$C_s = 1 - e^{-\mu z}$$

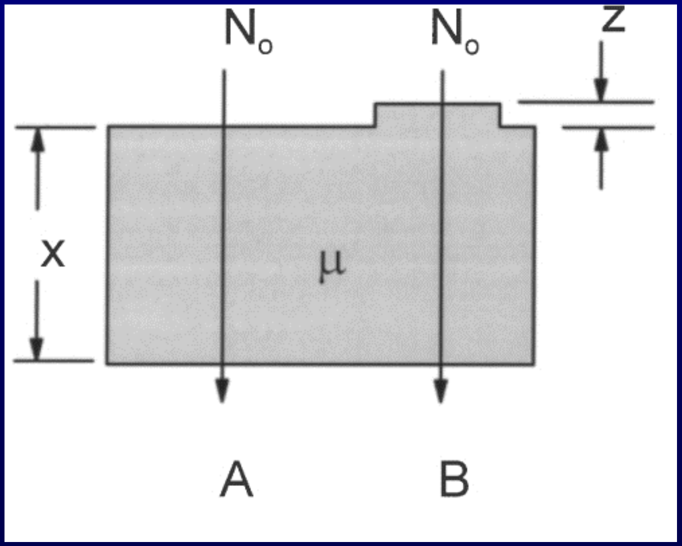


Fig 10-2A, Bushberg et al. 2nd Ed

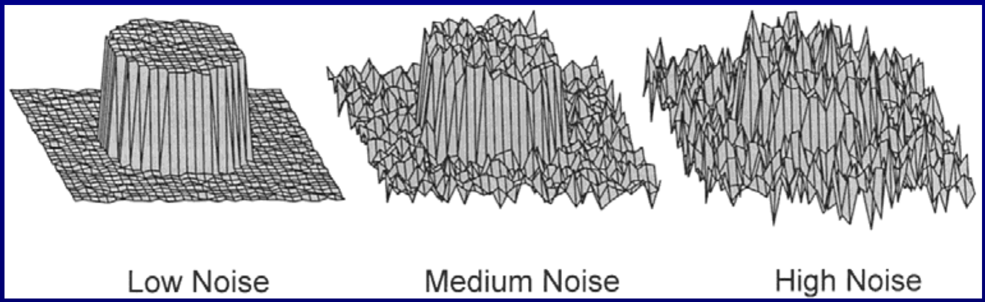
Noise interferes with our ability to detect contrast

Quantum noise: random uncertainty in the signal

$$\sigma = \sqrt{N}$$

$$SNR = N/\sigma = \sqrt{N}$$

Exposure (mR)	*Photons /100µ X 100µ pixel*	*Noise (%)*
1.0	1333	2.7
0.1	133	8.6
0.01	13	27.4



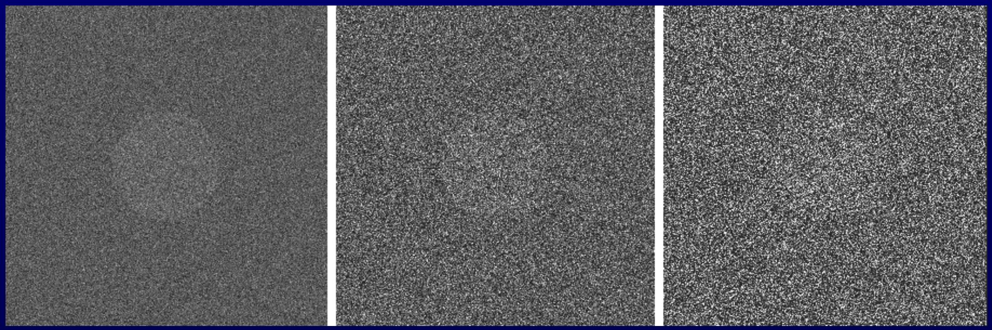
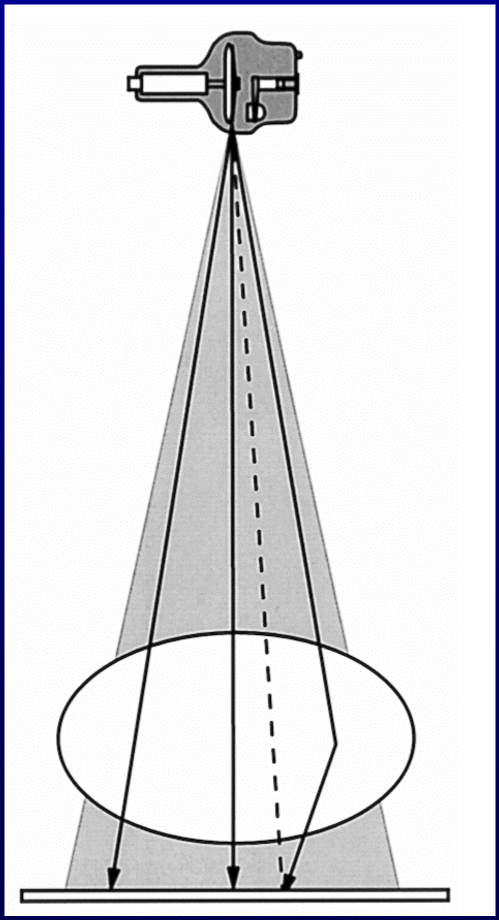


Fig 10-23 and 10-30A-C, Bushberg et al. 2nd Ed

Solution: increase exposure factors!

Scatter also degrades contrast, but cannot be corrected by increasing exposure factors



$$C_0 = (A-B) / A$$

$$C = C_0 / (1+S/P)$$

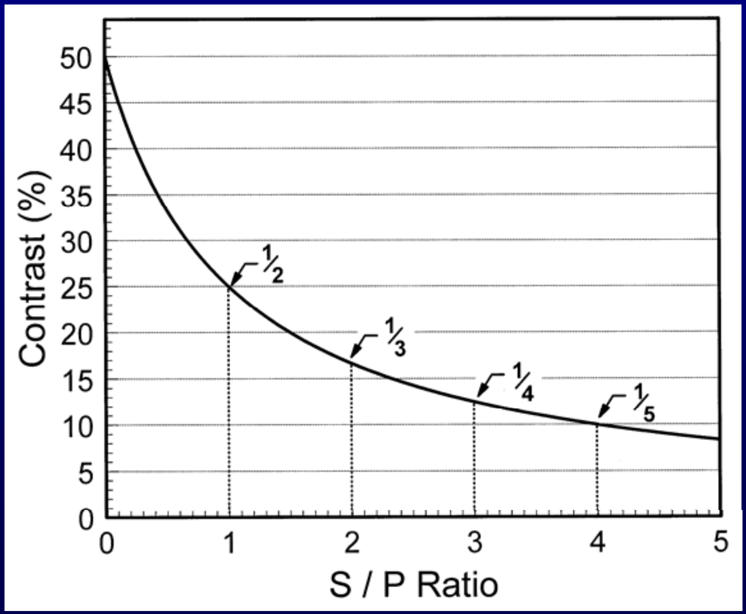
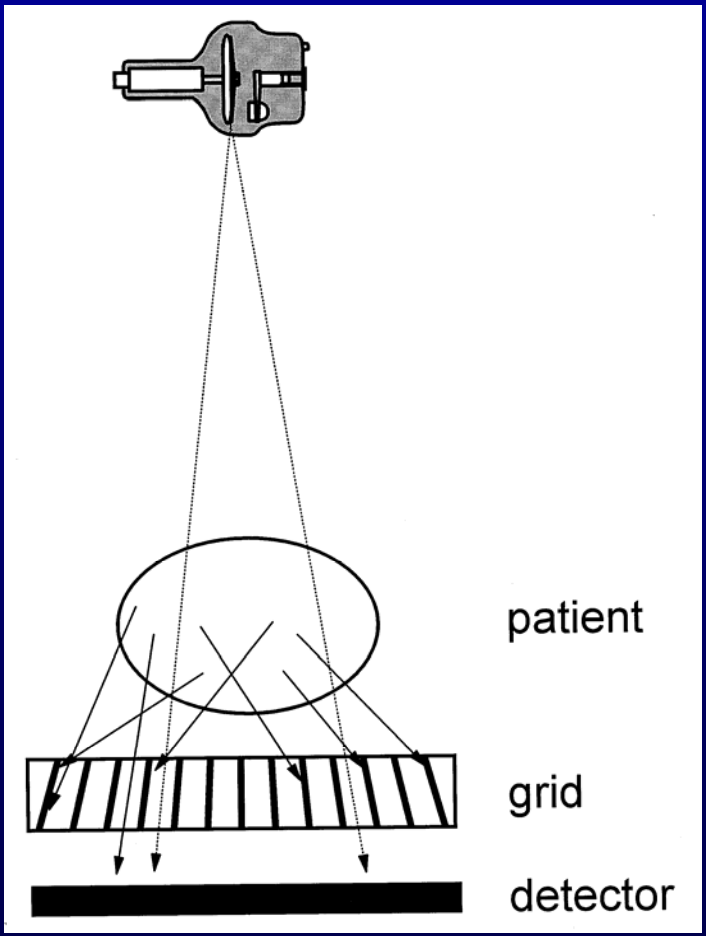
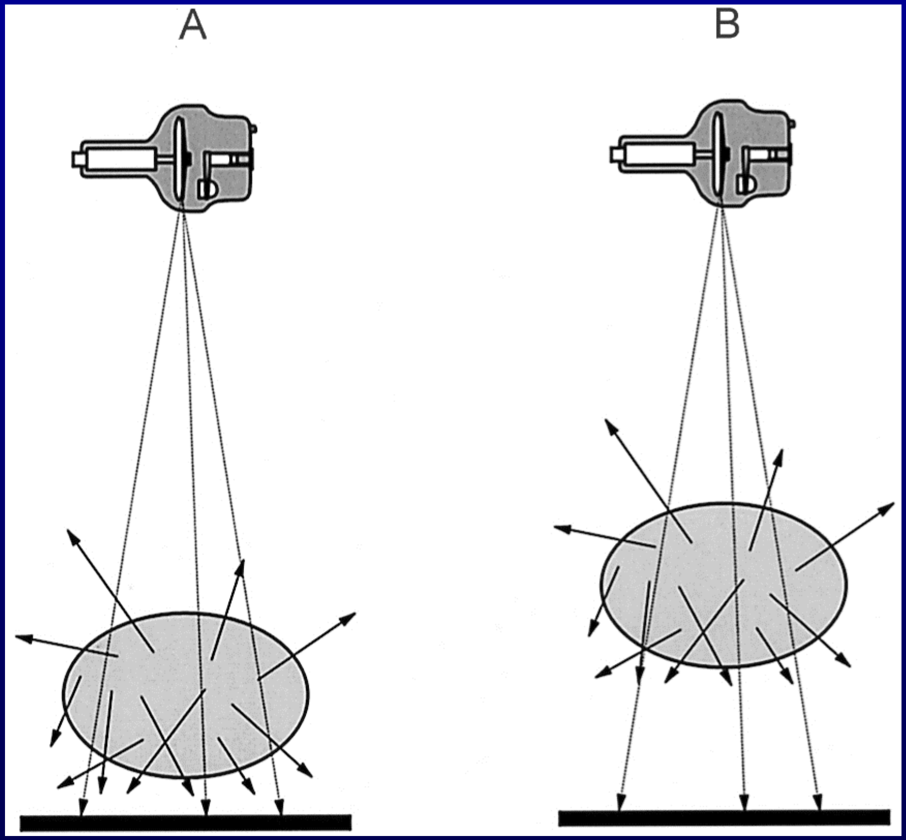


Fig 6-22A and 6-24, Bushberg et al. 2nd Ed

Scatter control methods



Scatter reduction grid



Air gap technique

Fig 6-30, Bushberg et al. 2nd Ed

Use of grid has penalties for dose and image quality

- Grid lines block some of the primary radiation
  - *For screen-film receptors, exposure factor needs to be increased by the Bucky Factor to produce the same optical density (OD)*
  - *Exposure factor must be increased at least by grid transmission factor for digital receptors to maintain the same noise properties.*
- Grid lines are projected into the imaging plane
  - *May be visible depending on the grid rate and detector sampling rate*
  - *Can cause aliasing artifacts with other periodic features in the original image or in down-sampled versions of the image*
- The grid must be aligned properly with respect to the central axis of the x-ray beam to avoid "grid cutoff"

The geometry of the projection affects patient dose and image quality

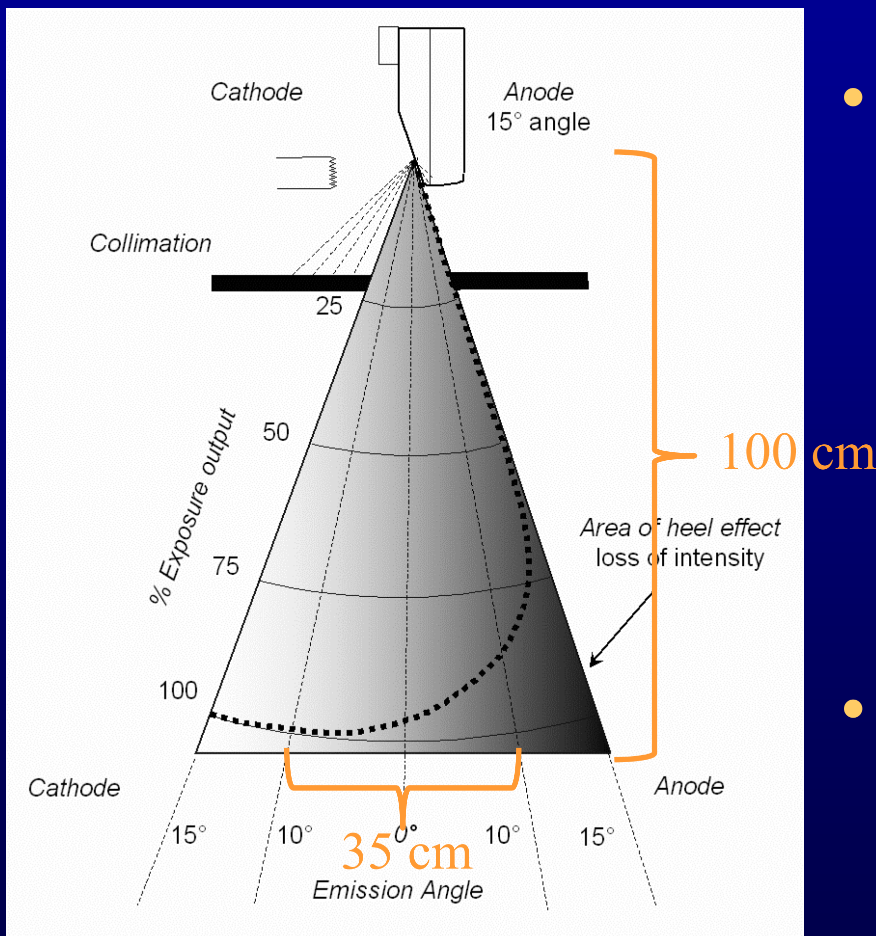


Fig 5-17, Bushberg et al. 2nd Ed

- Non-uniformity of the x-ray field
  - *Isotropic source projected on flat plane*
    - 3% exposure reduction
  - *Heel effect*
    - 13% exposure reduction
- We can use the heel effect to our advantage
  - *Anode up for Chest exam*

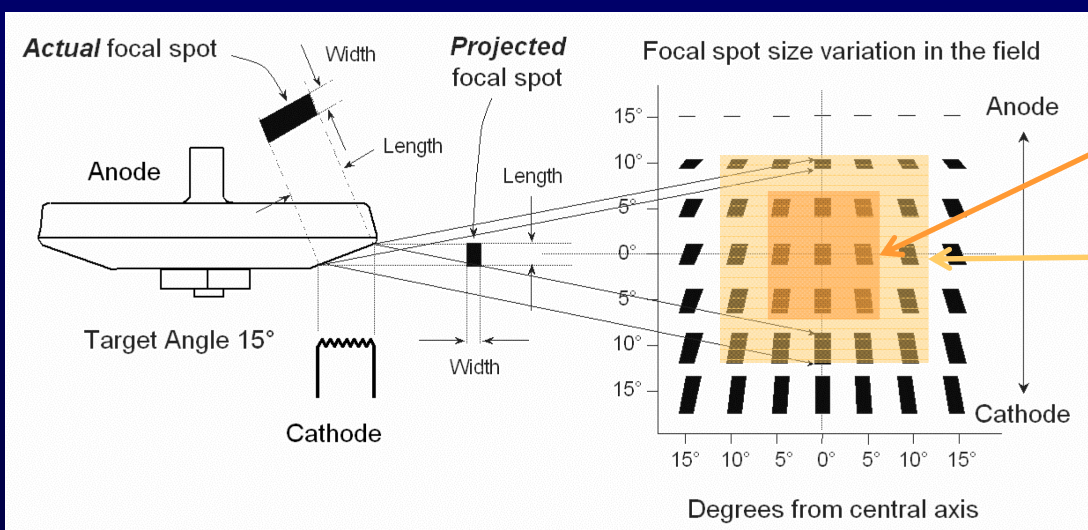
The geometry of the projection affects patient dose and image quality (continued)

- Off-axis geometric distortion
  - *Clinical features*
  - *Focal spot*
- The magnitude of geometric effects depends on
  - *Source-to-Image Distance (SID)*
  - *Source-to-Skin Distance (SSD)*
  - *Source-to-Object Distance (SOD)*

f=F[(SID/SOD)-1]

f=F(M-1)

Best sharpness near imaging plane!



SID=180cm

SID=100cm

Fig 5-15, Bushberg et al. 2nd Ed

Patient dose also depends on SID and SSD

- To deliver a given exposure in the imaging plane, mAs has to make up for inverse square law and attenuation from the patient.
  - *$(180cm/100cm)^2=3.24X$*
  - *Patient attenuation is a constant factor*
- At same tube output, patient entrance exposure is lower for the longer SID
  - *$ESE_1/ESE_2=[(180cm - T)/100cm - T)]^2$*
  - *4.16X for 23cm thick patient*
- Longer SID delivers same exposure in imaging plane at 78% ESE

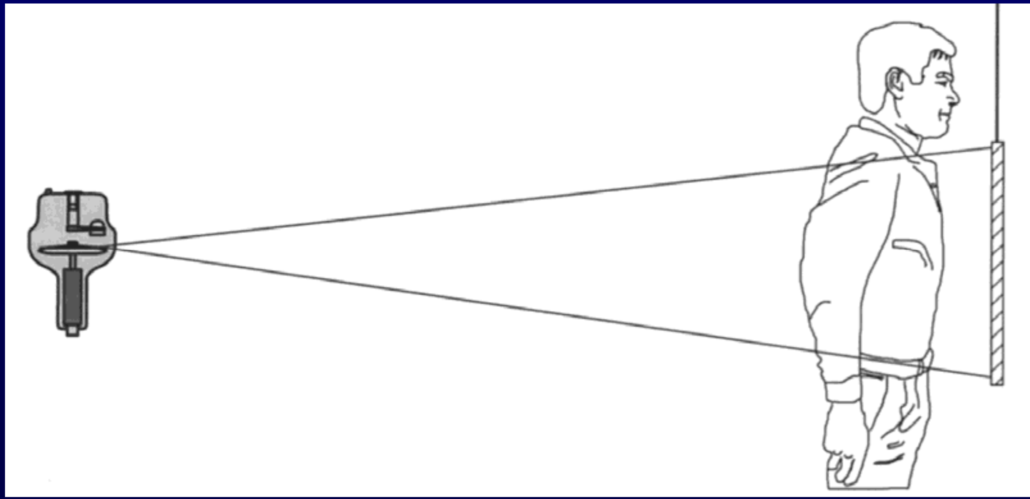


Fig 12-6, Bushberg et al. 2nd Ed

The capacity of the image receptor to faithfully reproduce the projected features affects patient dose and image quality

- The Detective Quantum Efficiency (DQE) is the overall indicator of the receptor's ability to transfer information
- An inefficient image receptor requires more radiation dose in order to produce the same quality output as an efficient receptor.
- Image quality can be described in terms of signal, noise, contrast, sharpness, and artifacts.
  - *The image receptor can adversely affect each of these.*
  - *Digital image processing can modify each of these.*

References

- Bushberg JT, Seibert JA, Leidhold EM Jr, and Boone JM. "The Essential Physics of Medical Imaging." 2nd Ed. Lippincott Williams and Wilkins: Philadelphia, PA. 2002. 933 pp.
- Wolbarst AB. "Physics of Radiology." 2nd Ed. Medical Physics Publishing: Madison, WI. 2005. 647 pp.

Learning Objectives:

1. Review fundamental principles of radiographic imaging systems.
2. Consider how these principles influence patient dose and image quality.
3. Provide the groundwork for dose and image quality optimization.

Radiography: Equipment Design and Siting

Charles E. Willis, Ph.D. DABR FAAPM
Associate Professor
Department of Imaging Physics
The University of Texas M. D. Anderson Cancer Center
Houston, Texas

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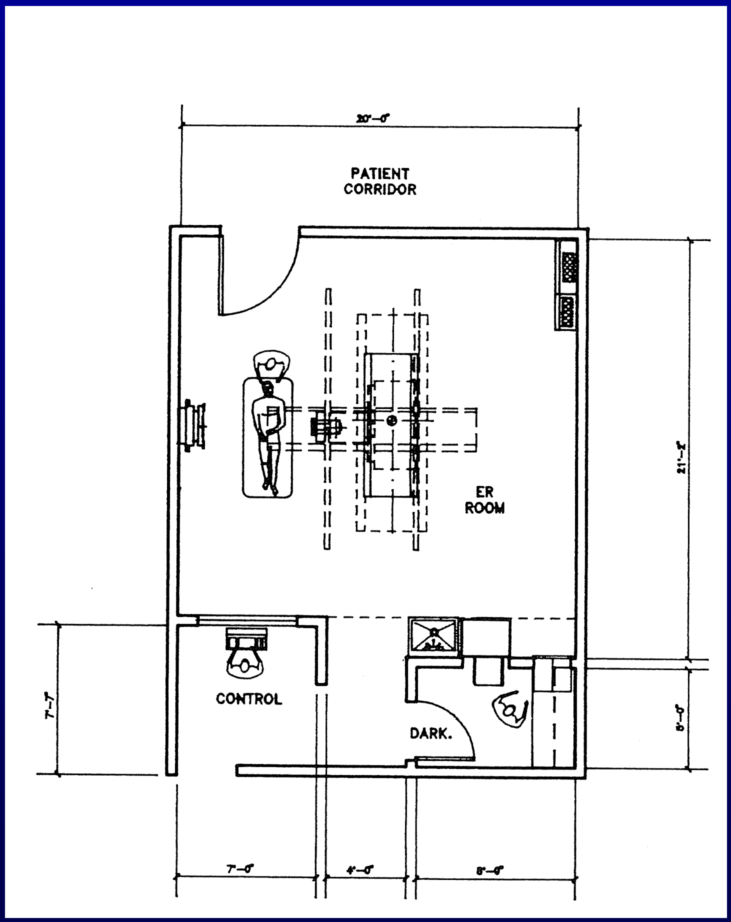
It may seem odd to consider equipment design and siting with respect to dose and image quality

- Consider, again, the purpose of the radiographic examination, that is,
  - *to position the patient in an x-ray beam of sufficient quality and quantity to project the anatomy of interest onto a flat detector of radiation.*
- Then aspects of the equipment design and siting that facilitate that purpose ameliorate dose and image quality.
- Conversely, aspects of equipment design and siting that impede that purpose compromise either or both dose and image quality.

"Exam rooms are often too small and rarely too large." (Roeck ,1991)

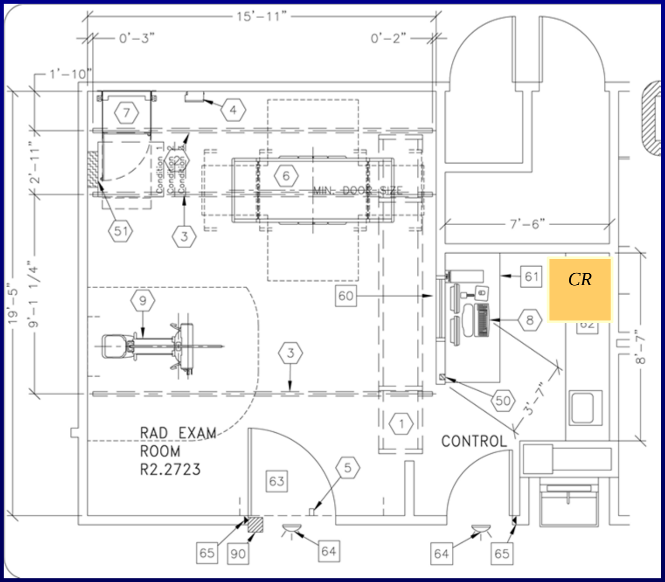


Room = 410 ft^2

Total = 486 ft^2

Fig 7a. Roeck (1991)

Darkroom = 40 ft^2



Room =320 ft^2

Total = 388 ft^2

(2012)

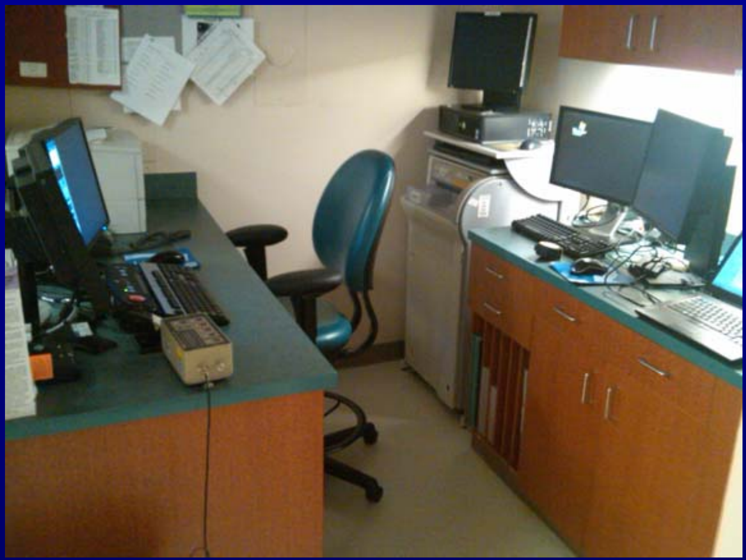
The radiographic room must be large enough to accommodate …

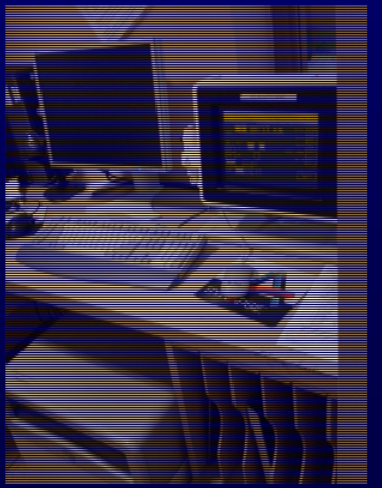
- The x-ray system
- Entry and exit of the patient, who may be in a wheelchair or on a stretcher
- Ancillary personnel, who may be transporting or assisting the patient
- The technologist, who is positioning the patient
- Auxiliary equipment, which might include oxygen supplies, patient monitors, infusion pumps, IV poles, portable shields, lead aprons.
- Supplies, such as bedding, cleaning agents, towels
- Waste containers

The greater the distance from sources to barriers, the less shielding required.

The control room must be large enough to accommodate …

- The technologist
- The operating console
- The acquisition station computer
- A general purpose computer for access to the radiology information system (RIS) and the PACS
- A paper printer (for those of us who are not yet paperless)
- A student technologist
- Ancillary personnel
- A computed radiography (CR) scanner
- CR Cassettes
- Grid caps/tunnels

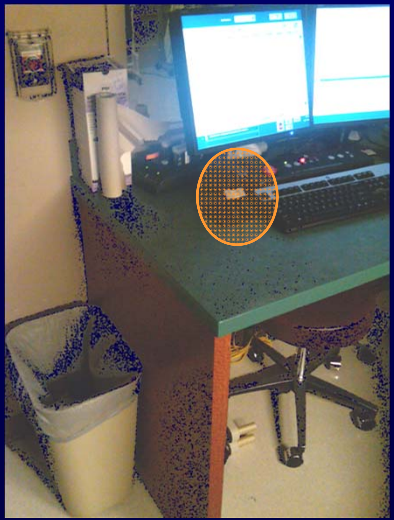




The layout of the equipment and operating console

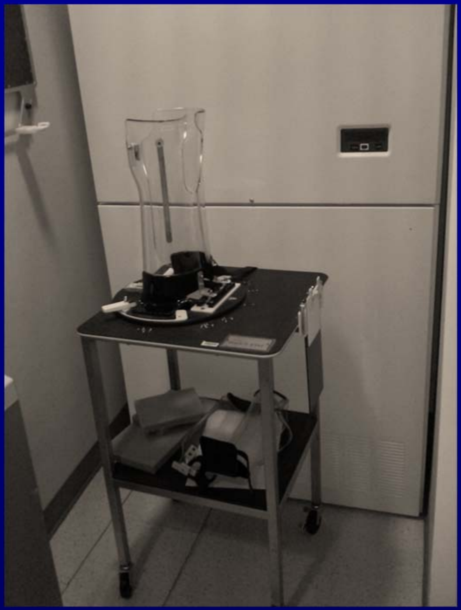
- Must allow unobstructed view of the patient during the examination
- Must *not* allow the technologist to initiate the exposure outside the operators room
  - *"The operator position during the exposure shall be such that the operator's exposure is as low as reasonably achievable (ALARA) and the operator is a minimum of six feet from the source of radiation or protected by an apron, gloves, or other shielding having a minimum of 0.25 lead equivalent material." (Texas)*

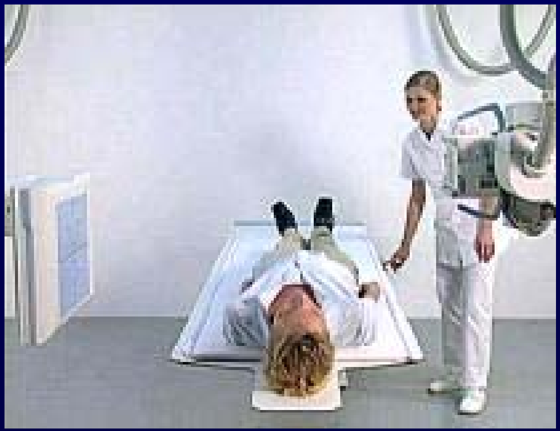




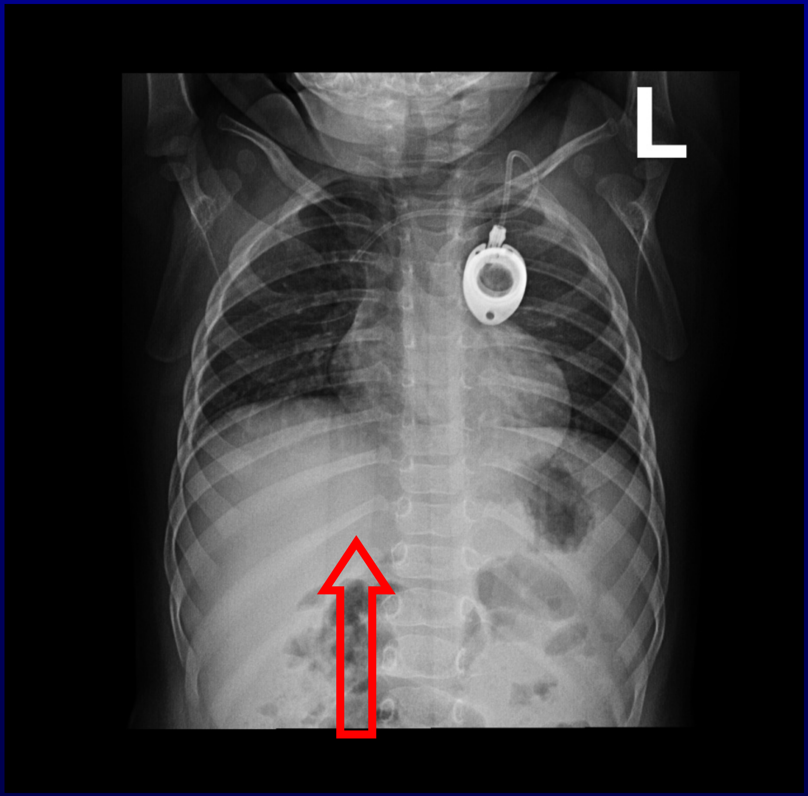

The radiographic system must immobilize the patient for the duration of exposure

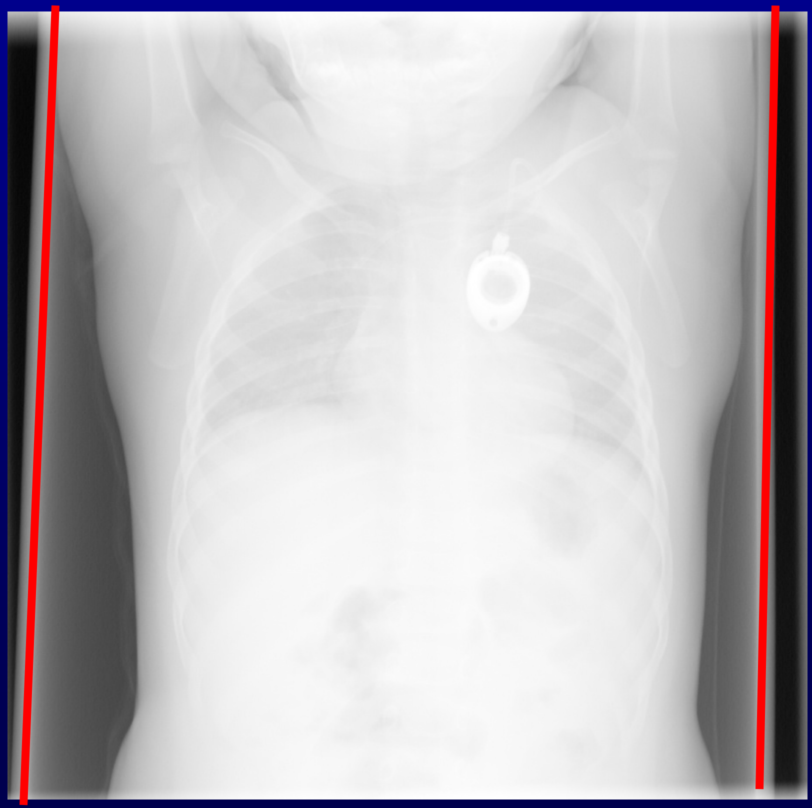







Pediatric immobilization device affects image quality and adds a dose penalty

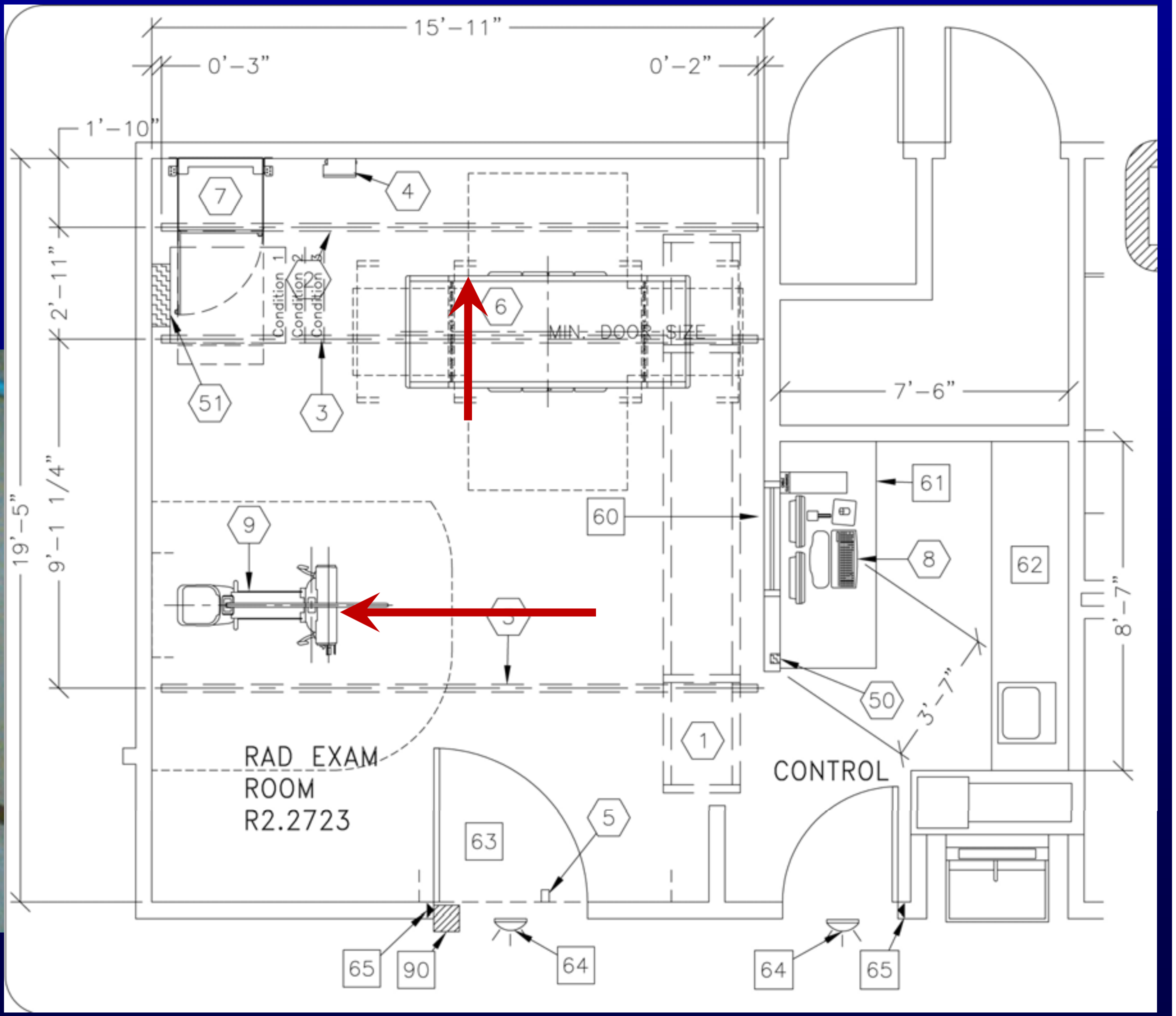




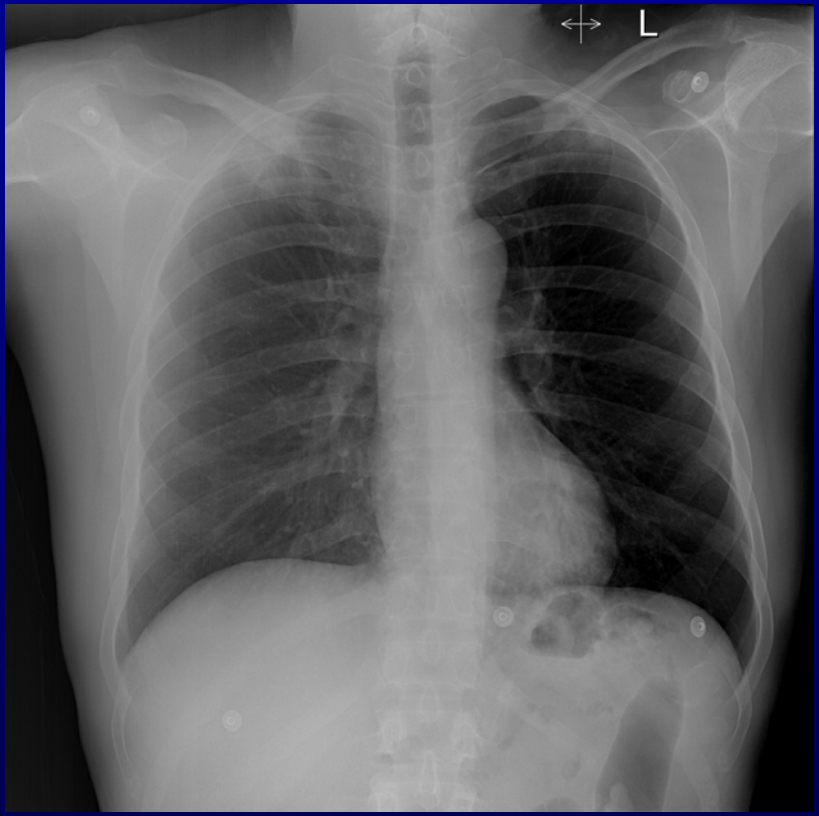
The overhead tube crane is suspended from rails which typically are hung from a steel unistrut grid.

The steel support structure must be rigid enough to maintain proper alignment x-ray central ray and the image receptor along several axes.

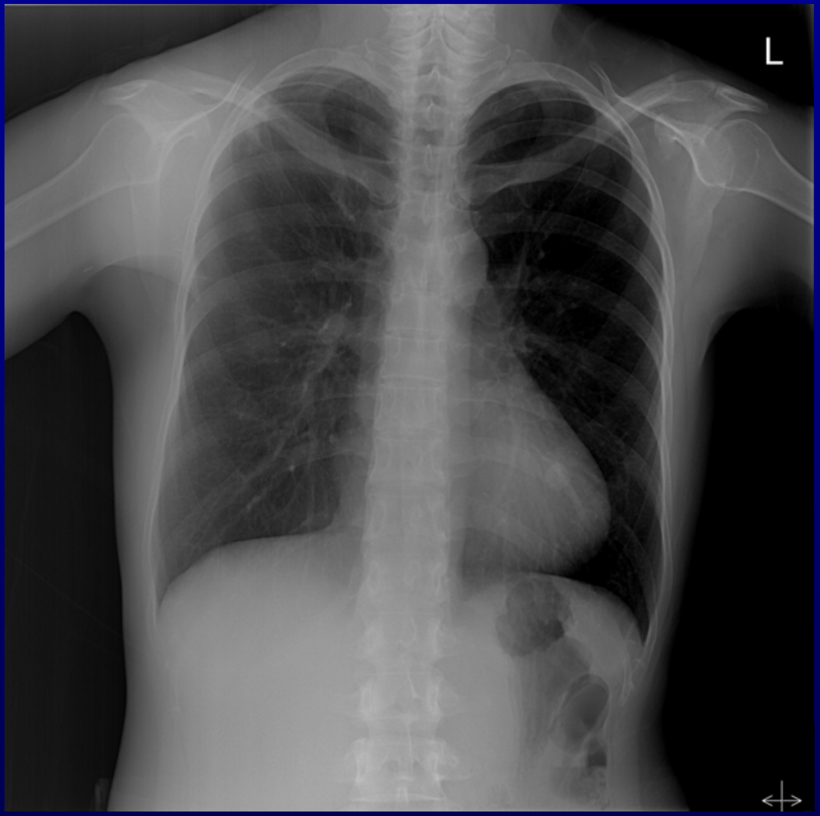
Tudor style?



Grid cutoff: discrepancy recorded in DICOM header, but system did not inhibit exposure.



100 cm focused grid
180 cm SID



180 cm focused grid
112 cm SID

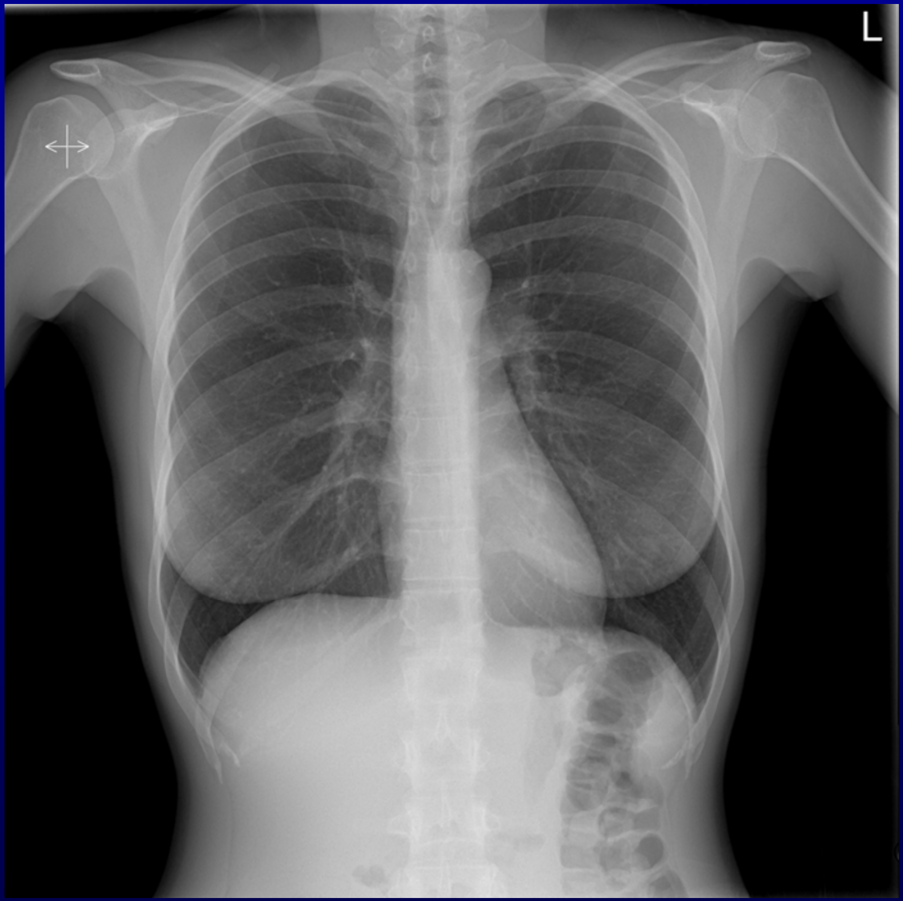
Do you think the grid is centered and perpendicular to the x-ray beam?

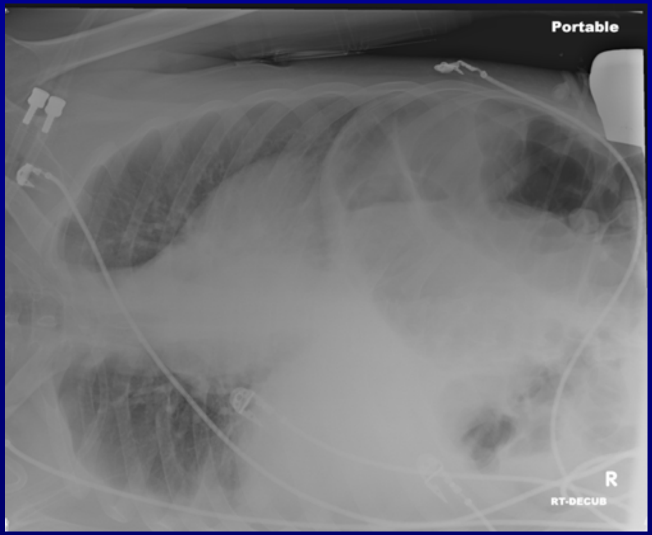
An overhead crane is not the only way to support an x-ray tube

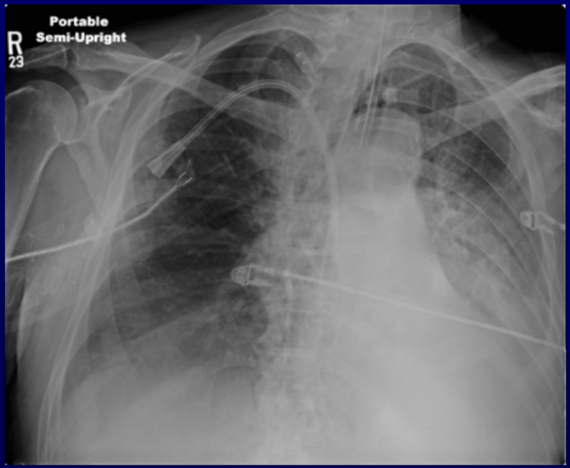
Can you tell just by looking whether these are digital or analog systems?

How is proper alignment maintained for crosstable views?

Equipment must accurately delineate the x-ray field







undercollimation

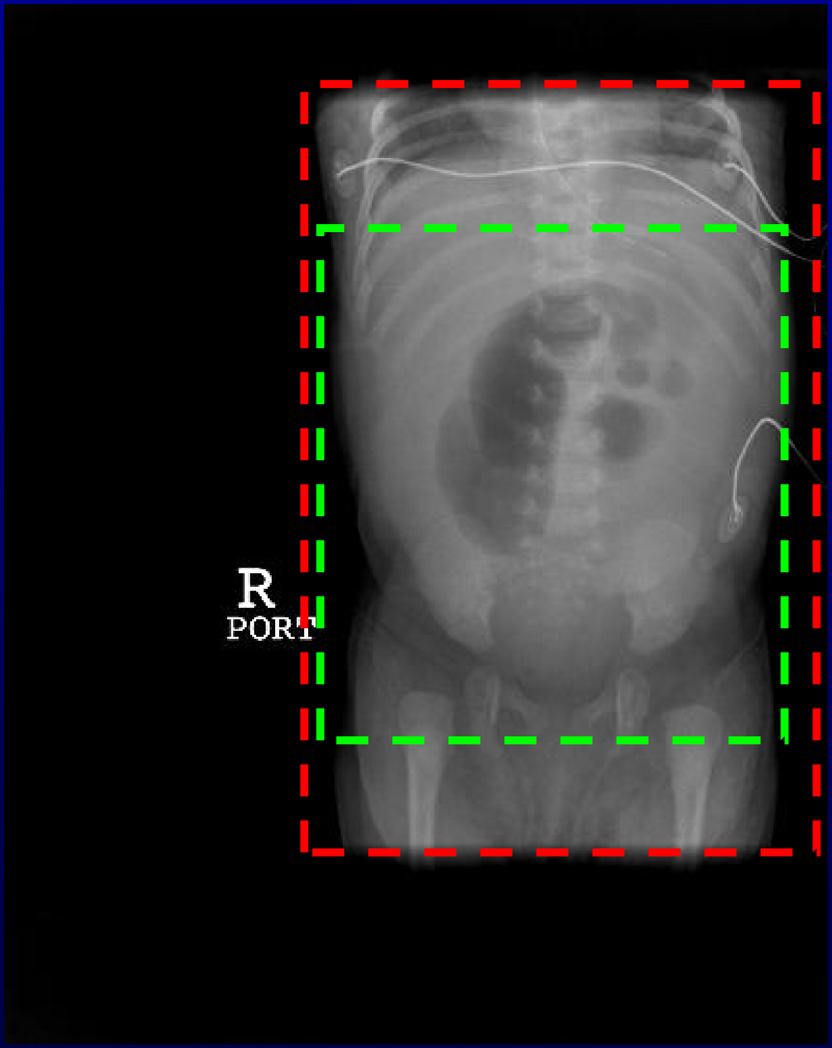
overcollimation

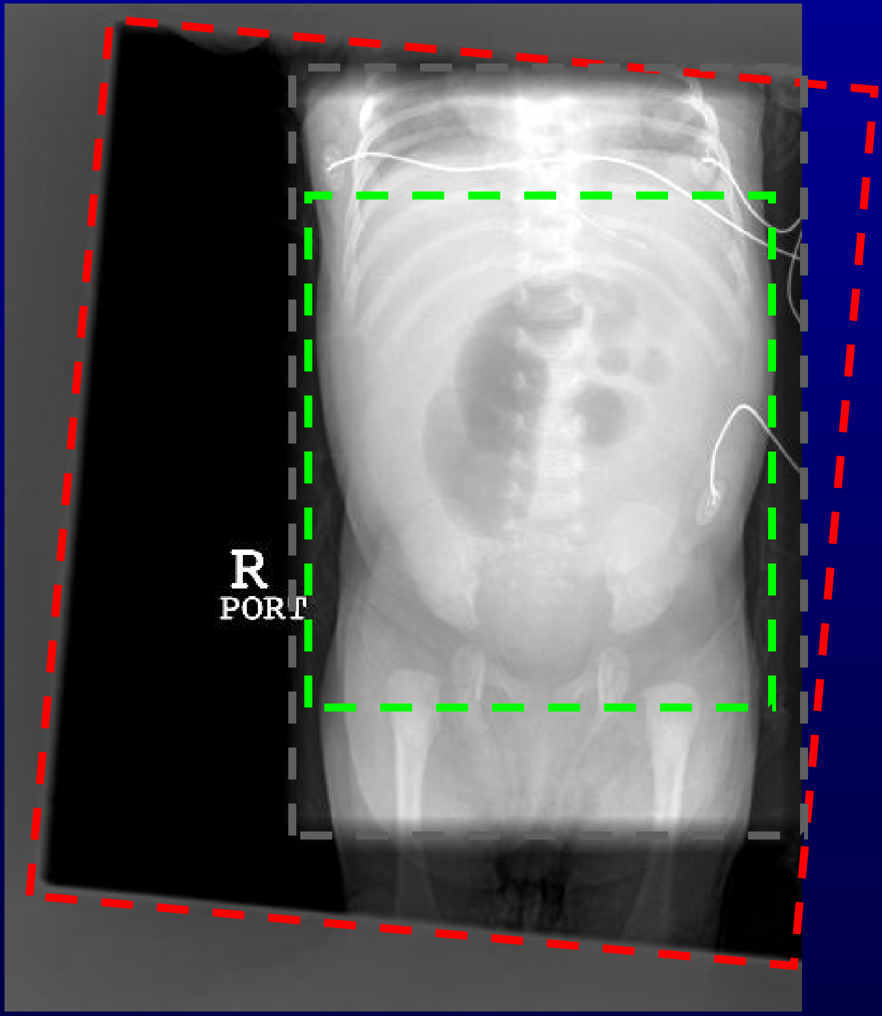
Collimators and automatic positioning features are subject to malfunction.

Light/X-ray field Congruence

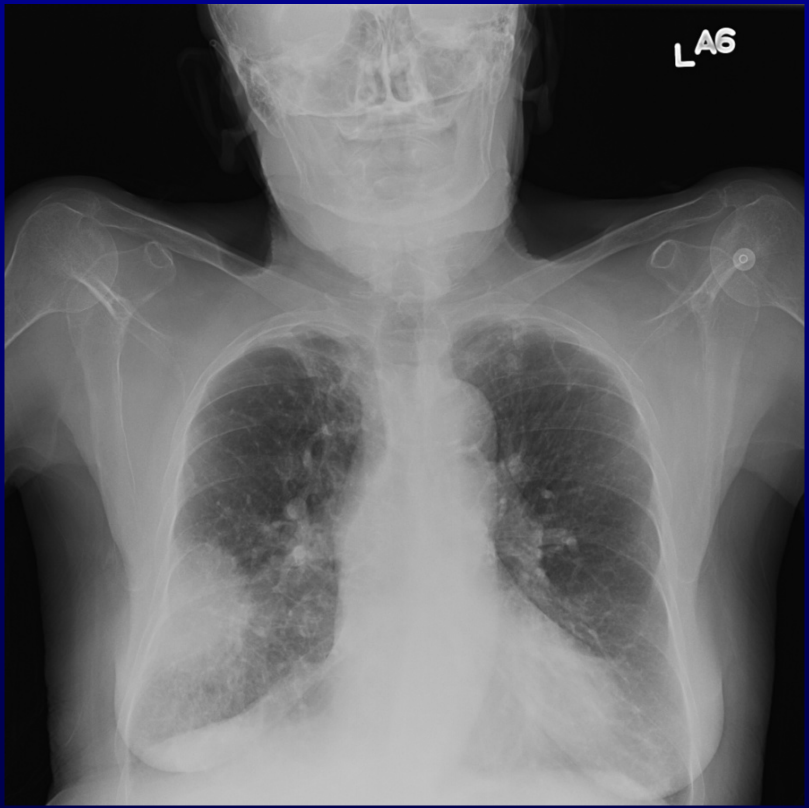
Detent 3 cm off

Where was the actual radiation field?





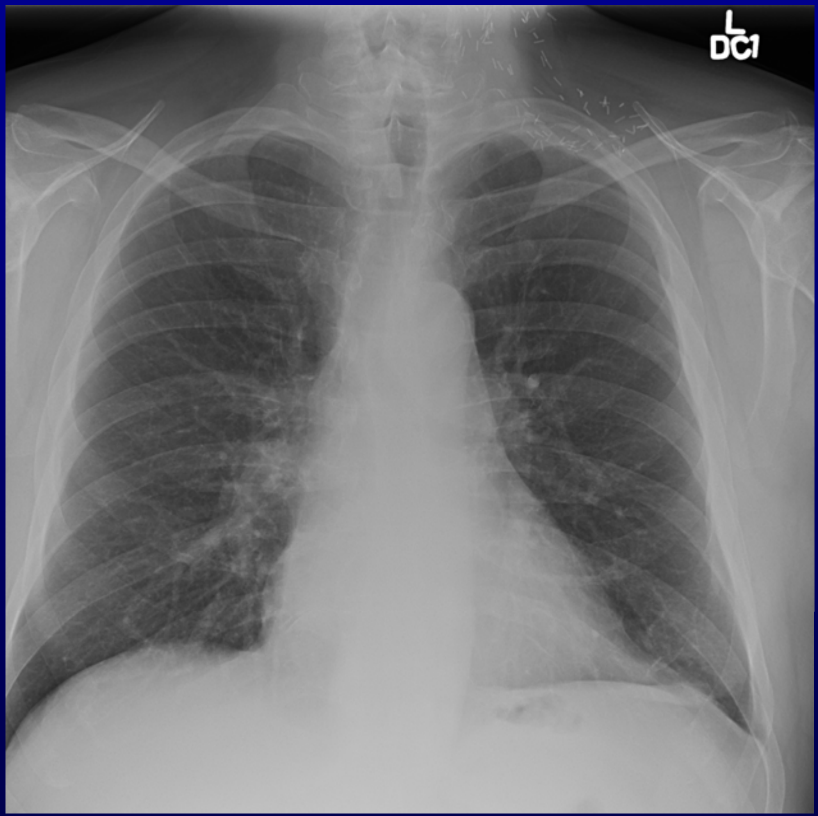
What was the radiation exposure to the head in this exam?



As seen by radiologist *As acquired …*

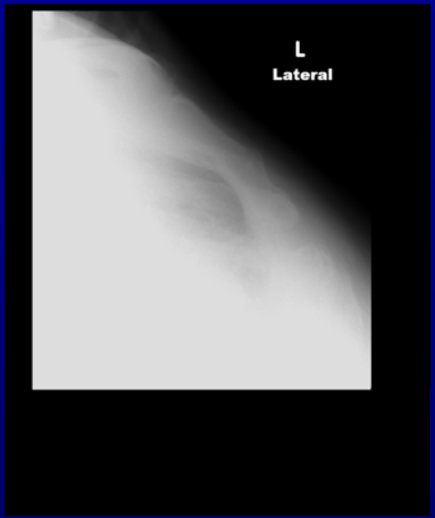
What if the receptor dimensions are not large enough to capture the anatomy of interest?

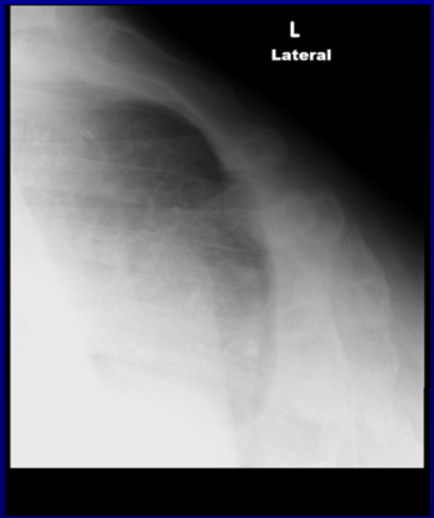
- There are good reasons why traditional receptor dimensions were 35cm X 43cm
- Some digital receptors are smaller (41cm X 41cm) or cannot be rotated.
- For large patients, a single view PA or AP chest must be acquired using two exposures, doubling the dose.

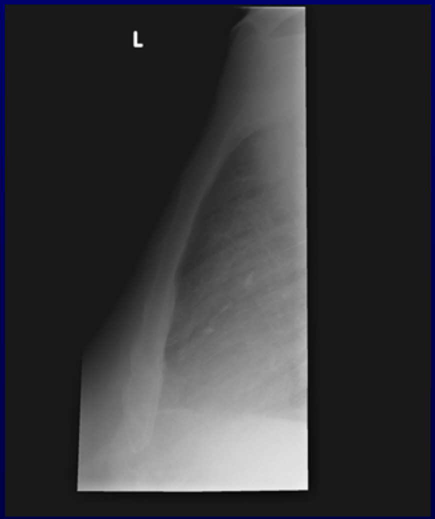


What if the receptor dimensions are larger than necessary enough to capture the anatomy of interest?

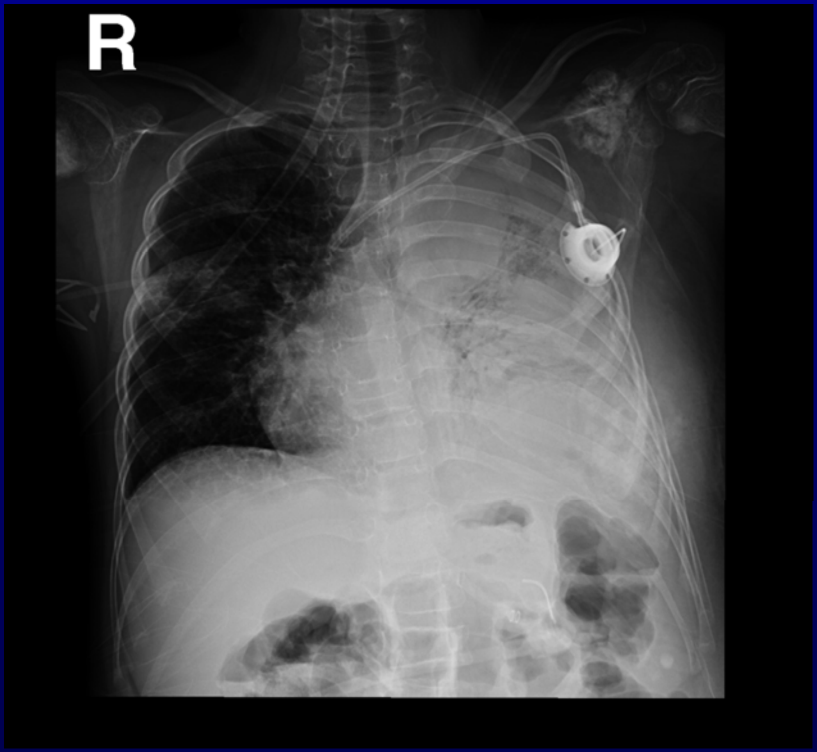
- There are good reasons why 20cm X 30cm receptors were available.
- Small FOV on a large image receptor is problematic.
- How do you perform neonatal bedside exams using a 43cm X 43cm image receptor?

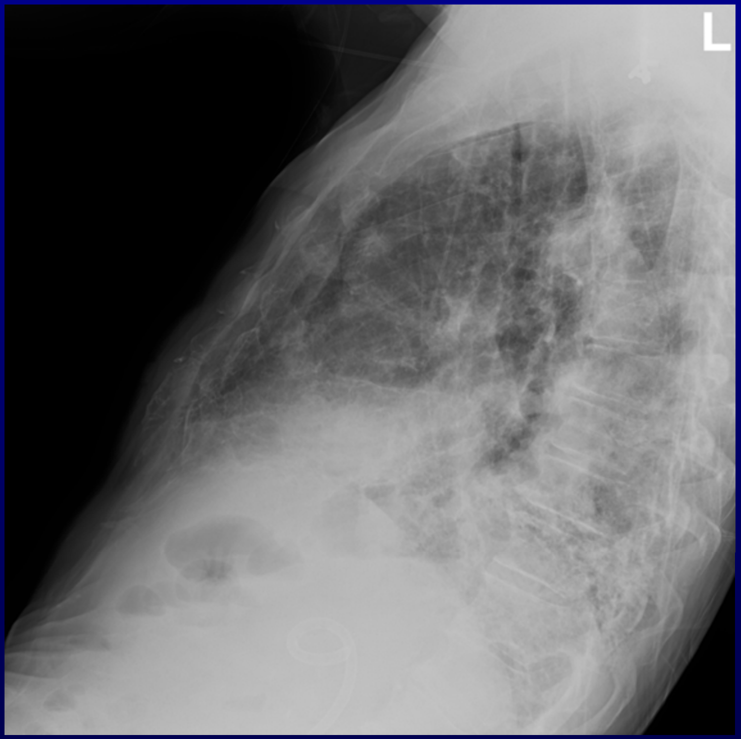






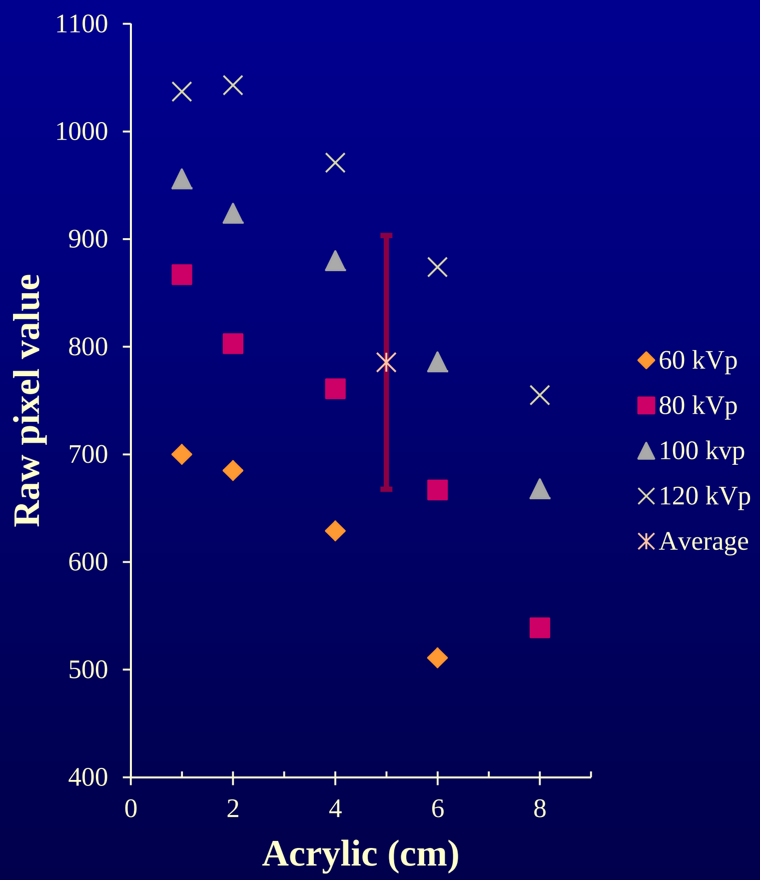
Two approaches for automatic exposure control (AEC): conventional vs. active monitoring a subset of detector elements (Sobol, 2004)

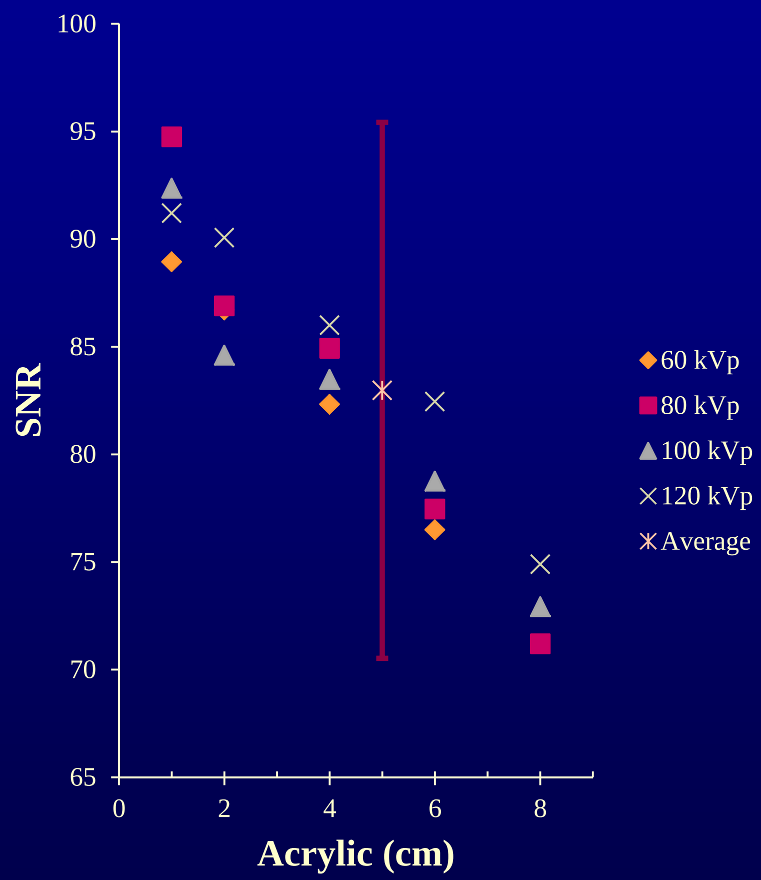




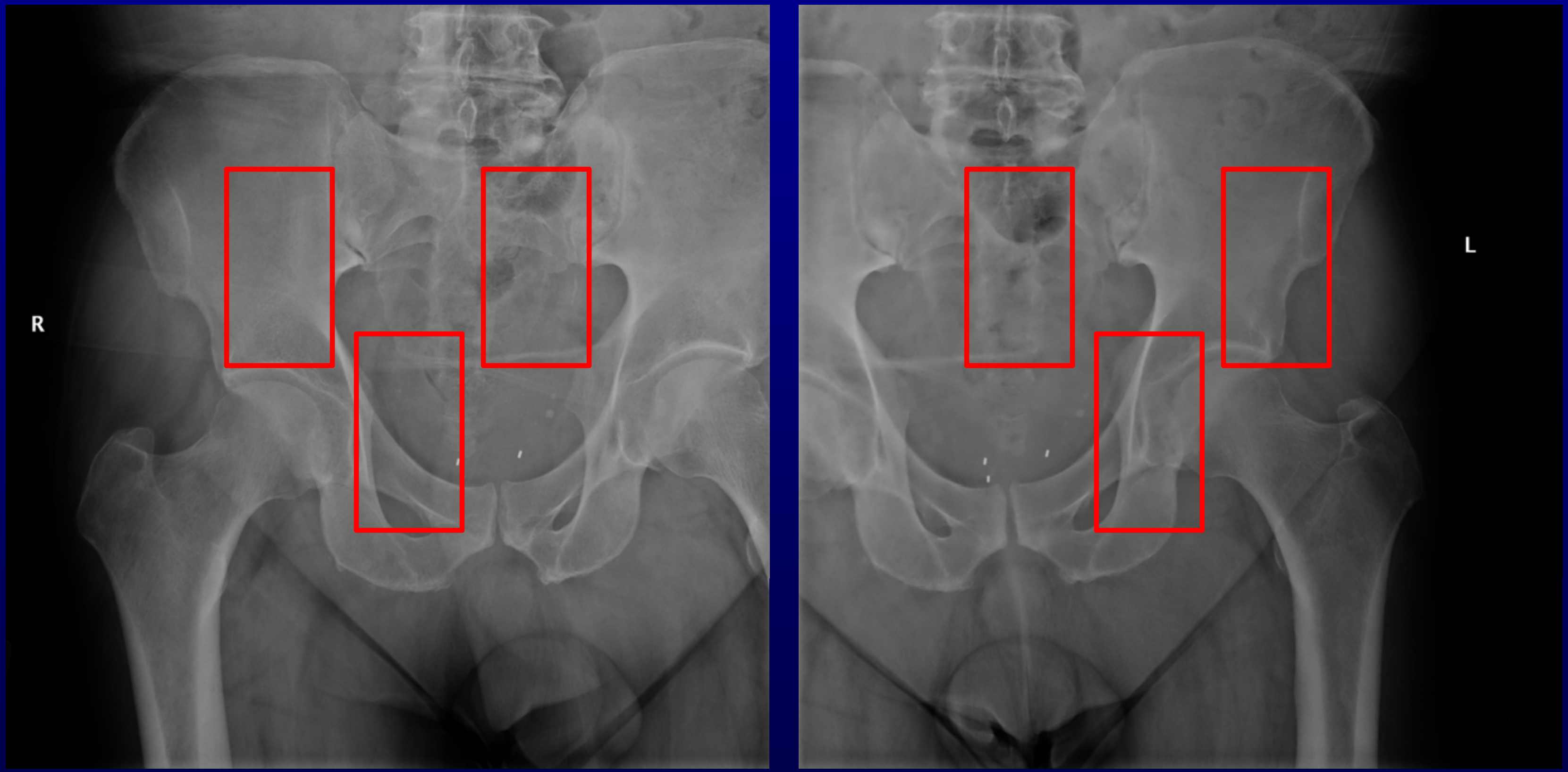
Both methods depends on proper positioning by the technologist!

What is the AEC regulating?





Should this exam have been performed using AEC?



27 mAs *15 mAs*

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- Sobol WT. Advances in and Specifications for Radiographic X-ray Systems. in *Specifications, Performance Evaluations, and Quality Assurance of Radiographic and Fluoroscopic Systems in the Digital Era*. Goldman LW and Yester MV eds. AAPM Medical Physics Monograph no. 30. Medical Physics Publishing: Madison, WI. pp. 1-68. (2004)
- Roeck WW X-ray Room Preparation: Layout and Design Considerations. in *Specification, Acceptance Testing and Quality Control of Diagnostic X-Ray Imaging Equipment.* Seibert JA, Barnes GT, and Gould RG eds. AAPM Monograph No. 20 American Institute of Physics: Woodbury, NY. pp 965-992. (1994)
- Bushong SC Specification/ Acceptance Testing of Radiation Shielding. in *Specification, Acceptance Testing and Quality Control of Diagnostic X-Ray Imaging Equipment.* Seibert JA, Barnes GT, and Gould RG eds. AAPM Monograph No. 20 American Institute of Physics: Woodbury, NY. pp 993-1015 (1994)

Learning Objectives:

1. Discuss aspects of radiographic equipment design and siting that influence patient dose and image quality.
2. Compare traditional systems with modern digital radiographic systems with respect to design and siting.
3. Provide some examples of the interplay of design and operation.